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FACTORS INFLUENCING CONFIGURATION AND PERFORMANCE OF MULTIPURPOSE MANNED ENTRY VEHICLES

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Introduction

Manned space missions are now moving beyond their infancy and into an area of more sophisticated activities. Mercury experience is in hand, and ahead are Gemini, X-20, and Apollo, each of which may be expected to contribute significantly to the advancement of technology for manned entry vehicles. In anticipation of requirements beyond these programs, we are led to inquire if each new space mission will continue to require a new entry vehicle.

For a number of reasons, among which are included the several years that transpire from conception to flight for any new entry vehicle, the acceleration that could possibly be afforded manned space activities, and in interests of economy, there would appear to be a place in the future for a reusable, multipurpose, manned entry vehicle. By multipurpose is meant that the vehicle would hopefully satisfy the essential requirements of a variety of missions, conceivably including not only peaceful and scientific endeavors, but possible military applications as well. This is perhaps not as visionary as it may first sound if there is acceptance of the idea of using an entry vehicle that, although it might not be ideally suited for a particular mission, would be sufficiently

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versatile to do the job without undue compromise to the mission objectives. A well-founded choice of the class of vehicle that is best suited for multipurpose use requires, in some respects, a more detailed definition of future missions than is currently available. But even should such information be in hand, it is too much to expect anything approaching universal agreement among the proponents of various entry vehicles in view of the existing divergence of opinion exhibited for specific, well-defined missions of the past and present. There is recognition, of course, that in the spectrum of foreseeable manned space activities, certain missions will require specialized entry vehicles, even should a multipurpose vehicle become a reality.

With these thoughts in mind, we will take a cursory look at some of the factors that might influence the design of a multipurpose entry vehicle with the hope of indicating a general class of entry vehicle that shows promise of affording this versatility without large penalties for aerodynamic performance.

An extensive survey of the literature was part of this study, as will be evident from the compilation of data in some of the figures. The list of references should be regarded as typical rather than exhaustive.

Symbols

A	ablation as primary heat protection method
C_L	lift coefficient
C_D	drag coefficient
g	deceleration, earth referenced

L/D	lift-drag ratio
M	entry mode involving pitch modulation in pullout (see text)
Q	heat load
$\dot{q}$	maximum heat rate
r	nose radius
R	radiative cooling as primary heat protection method
S	reference area
T	temperature
U	entry mode having no pitch modulation in pullout (see text)
V	velocity
V_E	entry velocity
W	weight
γ	flight-path angle
γ_E	entry angle
$\Delta\gamma_E$	difference in entry angle between undershoot and overshoot, i.e., corridor width

Subscripts:

lim	limiting value
max	maximum value
rad	radiative heating
conv	convective heating
A	ablative
R	radiating metallic
eq	radiation equilibrium

0	at L/D = 0
P	payload
26	at V_E = 26,000 ft/sec
T	total, i.e., radiative plus convective

Discussion

Entry Velocity

Low earth orbits will continue to be attractive to a number of future missions, such as the near-earth manned space station. High earth orbits, circular and highly elliptic, are receiving study for both military and exploratory objectives, wherein altitude flexibility may be desired from mission to mission. As orbit or apogee altitude is increased to conform to these mission requirements, entry velocity may increase decidedly, as illustrated in figure 1, approaching 34,000 ft/sec at the altitude for a 24-hour orbit. The range of entry angles of interest for manned operations (about 0° to 10°, as will be shown later) is seen to have little effect upon entry velocity, except when orbit or apogee altitude is within about 1000 miles or less of the earth.

At escape velocity and beyond we encounter the regime of lunar and planetary missions. Figure 2 presents the familiar picture of minimum entry speeds to Earth in return from Mars and Venus as a function of transit time[1]. Velocities at least as high as about 45,000 ft/sec are of interest because of the large reduction in return time afforded by small increases in velocity above the minimum.

On the other hand, justification for velocities in the upper hyperbolic regime will be more difficult to come by unless there is a major breakthrough in propulsion systems, primarily because of the small decrease in return time associated with large and costly increases in velocity. A more important question, perhaps, is what entry velocity can man endure without exceeding his deceleration tolerance. An upper limit is obtained by letting $L/D = \infty$. This limiting velocity is shown in figure 3 as a function of the deceleration that is permitted. In the real case, the entry velocity will have to be less than that given by this curve.

Clearly, in the absence of propulsive braking prior to entry, future manned space missions stimulate interest in entry velocities extending from circular well into the hyperbolic regime. The ability to enter over this range of velocities would be a most desirable feature of a multipurpose entry vehicle. Accordingly, entry velocity has been selected along with the hypersonic lift-drag ratio as a primary variable in this review.

Entry Modes

The material involving trajectory calculations that is presented herein deals primarily with two entry modes. These two should serve the purpose of this paper in bringing out salient features of the environment and vehicle performance.

In mode U entry is initiated with the vehicle in the trimmed positive lift condition for either $(L/D)_{max}$ or $C_{L_{max}}$. (Use of negative lift in the initial entry phase is considered herein to be a procedure that is resorted to in emergency only.) A constant L/D trajectory is flown from entry to pullout. At this point the vehicle is rolled so as to maintain a constant altitude flight path, including the use of negative lift, i.e., roll or lift vector modulation is assumed in this phase of the trajectory. This maneuver is maintained until the vehicle is unable to generate sufficient lift to sustain flight at that particular altitude. An equilibrium glide maneuver at either $(L/D)_{max}$ or $C_{L_{max}}$ is then initiated and flown to the landing point. The assumed limit on decelerations is 12g. The overshoot criterion is a no-skip entry within one pass, and the use of negative lift after pullout is permitted.

In mode M, the overshoot criterion is the same as for mode U. Otherwise, mode M employs pitch modulation in pullout. In undershoot, pitch modulation is employed once 12g is reached so as to maintain this g level through $C_L = 0$, and into the negative lift phase until negative $(L/D)_{max}$ is reached, following which roll modulation at constant altitude is employed. The remaining flight is the same as for mode U.

In all cases entry is assumed to begin at 400,000 feet and the earth is considered to be spherical and nonrotating.

Simulator studies of mode U have indicated it to be feasible. Mode M introduces additional complexities that have not been excercised to the same extent, particularly that portion of the entry immediately after the point for $C_L = 0$ during which minor excursions from the required maneuver could introduce excessive deceleration. Otherwise mode M appears reasonable and should serve to demonstrate the influence of pitch modulation during pullout. Reference 2 provides a summary of pertinent guidance and control studies.

Deceleration

Once the upper limit on permissible deceleration has been fixed, there is a natural tendency to exhibit little interest in g-alleviation below this limit that may be derived from increased L/D. Nevertheless, it is instructive to take a somewhat broader look at the deceleration picture. An indication of the scope and general trends of decelerations to be experienced during entry (by mode U) is presented in figure 4. In the left-hand side of the figure, peak g's are shown as a function of entry angle for two entry vehicles, one with an $(L/D)_{max}$ of 0.5 and the other with an $(L/D)_{max}$ of 2. The solid curves are for entry at 26,000 ft/sec and the dashed curves for 46,000 ft/sec; the peak g's given by these curves are those experienced during the course of deceleration prior to establishing the equilibrium glide. It is evident that as orbital speed is exceeded, peak g becomes increasingly sensitive to change in entry angle, thus requiring close attention to possible sources of error in flight path angle just prior to entry. For manned entry that employs atmospheric braking only, entry angle will be limited to something between 0° and about 10°.

A closer inspection of the peak g's experienced at overshoot is afforded on the right in figure 4 (actually at pullout, but essentially peak values). The dashed curve represents peak g's encountered in an equilibrium glide following deceleration to orbital speeds and is shown for reference. The solid curves serve to illustrate that increasing entry velocity brings about marked increase in peak g's at overshoot, particularly at low L/D. At much higher velocities, the peak g's at overshoot are sizeable even for high L/D; for example, at 60,000 ft/sec the peak g's at overshoot would approach 5 at values of L/D of 2 or so. The important implication is that in the event of an emergency in which it would be desirable to avoid the higher peak g's near undershoot by entering nearer the overshoot boundary, the peak g's cannot be substantially reduced below those indicated without resorting to entry modes that generally involve skip. Such emergencies and, in fact, the peak g that would be experienced in the average entry between undershoot and overshoot lead to an interest in the alleviation in peak g that can be brought about by L/D. These considerations, although at best of secondary importance in vehicle choice, turn interest toward an L/D at least as high as 1 because of the sizeable reductions in peak g's with increasing L/D that occurs in the low L/D range at overshoot and at any given value of entry angle between undershoot and overshoot.

All of the results in figure 4 are for entry at $(L/D)_{max}$; however, the general conclusions are essentially the same for entry at $C_{L_{max}}$ (ref. 3).

Corridor Width

The width of the entry corridor between undershoot and overshoot is of interest primarily from the standpoint of guidance requirements and flexibility of operation. Figure 5 gives some feel for the width of corridor as a function of hypersonic $(L/D)_{max}$. On the left, corridor width for entry mode U only is presented in terms of the difference in entry angle between undershoot and overshoot, $\Delta\gamma_E$. Increasing entry velocity is shown to reduce the width of the corridor from about 10° maximum at orbital entry speeds to about a 2° maximum at 46,000 ft/sec; the loss in corridor width from entering at $C_{L_{max}}$ rather than $(L/D)_{max}$ is relatively small. A value of $\Delta\gamma_E$ of about 1° is generally considered to be the minimum acceptable without excessive demands on guidance requirements. On this basis, entry by mode U has a velocity potential somewhat beyond 46,000 ft/sec for vehicles with $(L/D)_{max}$ of about 1 or greater.

The advantages to corridor width in entering by mode M as compared to mode U are shown on the right in figure 5. Here the corridor width is given in terms of statute miles to afford some insight into the relation of miles to $\Delta\gamma_E$ (compare mode U curves). Major increases in corridor width can be realized by resorting to mode M provided hypersonic $(L/D)_{max}$ is in excess of about 0.3 or so. Figure 6 shows that the use of such a mode also extends the permissible entry velocity for a given L/D and specified corridor requirement, low L/D and extremely small corridor widths excepted.

The advantages to be gained from L/D again direct attention toward an $(L/D)_{max}$ of about 1 or greater, although L/D as low as

1/2 cannot be ruled out for mode M on a corridor-width basis for velocities less than about 50,000 ft/sec or so.

Relation of $(L/D)_{max}$ to $C_{L_{max}}$ and to L/D at $C_{L_{max}}$

An attractive goal in the design of a multipurpose vehicle would be the capability of having high C_L and good L/D at high C_L simultaneously. This would afford the advantages of operation at high C_L (for example, reduction of heat loads) while avoiding undue compromise to lateral ranging resulting from a possible major reduction in L/D caused by operation at high C_L. The extent to which this goal may be realized in practice gives rise to an interest in the relation of $(L/D)_{max}$ to $C_{L_{max}}$ capability, and the relation of $(L/D)_{max}$ to L/D capability at $C_{L_{max}}$. Figure 7 gives some insight into these relations. The effect of $(L/D)_{max}$ on $C_{L_{max}}$ is considered at the top. An estimate labeled Newtonian envelope is shown along with a compilation of experimental data for a variety of entry vehicle shapes. These data are restricted to those shapes showing relatively good $C_{L_{max}}$ capability. (See ref. 3 for a more complete picture.) The main point to note is that the estimate and the experimental data direct interest toward an $(L/D)_{max}$ near 3/4 or greater. The peak near $(L/D)_{max}$ of 3/4 is partly realistic and partly deceptive in that at these and lower values of $(L/D)_{max}$, the vehicles are chunky and tend to shift the more realistic reference area from planform area (as used here) to base area. However, use of base area in the low $(L/D)_{max}$ regime would not alter the conclusion[3].

The effect of $(L/D)_{max}$ on L/D at $C_{L_{max}}$ is shown at the bottom of figure 7. The experimental data and the estimate[3] direct interest toward an $(L/D)_{max}$ of about 1 or greater when considered solely in the light of having good L/D potential at $C_{L_{max}}$. On the other hand, if a high-C_L roll-modulation mode of entry is employed, interest is confined to an $(L/D)_{max}$ in the vicinity of 1, since it would be difficult to justify the penalties for building in a high hypersonic $(L/D)_{max}$ capability that would not be used.

Heating

A multipurpose vehicle as considered herein is faced with the possibility that radiative heating may have a major contribution to the heat input when the entry velocities are considerably in excess of orbital speed. Figure 8 illustrates the relation of hypersonic $(L/D)_{max}$ and entry mode to maximum stagnation-point heat rates and heat loads for both radiative and convective heating at entry velocities of 36,000 and 46,000 ft/sec. Related information on the heating at near-orbital speeds where the input is essentially all convective may be found in reference 3. The results shown herein assume a loading W/S of 35 and a nose radius of 1 foot unless otherwise specified. The value of W/SC_L corresponding to entry at $(L/D)_{max}$ is approximately twice that for entry at $C_{L_{max}}$, and in each case the value of W/SC_L is assumed to be invariant with $(L/D)_{max}$. The results in figure 8 are for entry at $(L/D)_{max}$.

Entry mode M is seen to produce heating rates (top of figure) greatly in excess of those for entry mode U for both radiative and convective heating. Increasing $(L/D)_{max}$ accentuates this difference.

No heating rate results are shown for overshoot, but they fall well below the undershoot values.

The bottom of the figure shows that, in undershoot, entry mode M reduces the convective heat load slightly but increases the radiative, markedly so at 46,000 ft/sec. In overshoot, the heat load is seen to be dominantly convective; at 36,000 ft/sec the radiative contribution in overshoot is too small to be indicated.

Figure 9 sums the radiative and convective contributions shown in figure 8 to obtain total heat rates and total heat loads. Except at low $(L/D)_{max}$, the total heat rates in undershoot are seen to be much higher for mode M than for mode U. Similarly, the total heat loads for mode M exceed those for mode U. This is not of major importance at 36,000 ft/sec and lower since the overshoot condition calls for a higher design heat load. However, at 46,000 ft/sec, the undershoot total heat load for mode M exceeds the overshoot total heat load at other than low $(L/D)_{max}$. Thus, the wider corridors shown earlier for mode M come at the expense of a more severe heating environment whose effects upon heat protection, weight, etc., must be weighed against the necessity for the increased corridor width. The contents of figures 8 and 9 also serve to indicate that from a heating standpoint, high $(L/D)_{max}$ is not an attractive approach to a multipurpose vehicle.

The heating results presented thus far have dealt with entry at $(L/D)_{max}$. Entry at high C_L is also of interest. An example of the effect upon stagnation-point heat load is given in figure 10. A vehicle with $(L/D)_{max}$ of 1 is assumed to be entering by mode U along the overshoot boundary, and the entry velocity is varied between orbital velocity and the maximum permissible entry velocity (zero corridor width and 12g at overshoot). Entry at high C_L is seen to reduce the radiative as well as the convective contribution, and to delay the onset of major radiative input to higher velocities. The reduction in the convective and radiative inputs is associated with both the reduced W/SC_L and the reduced L/D; however, the reduction in the radiative input is primarily associated with the reduced W/SC_L. In this example, entry at $C_{L_{max}}$ reduced the L/D by about 30 percent while W/SC_L was approximately halved.

These results, particularly those for entry at $(L/D)_{max}$, also demonstrate the formidable increase in heat inputs that can be expected in the upper hyperbolic velocity regime. In this regime heating may very well exert the major influence on, if not dictate, the vehicle design; moreover, this is a regime of considerable ignorance as to both problems and solutions. It thus seems wise to focus attention for the present on velocities below about 50,000 ft/sec as the potential realm of a multipurpose vehicle. This still admits of velocities sufficiently high to be of interest in planetary missions (fig. 2), yet not so high as to reduce the corridor width below minimum limits for entry mode U (fig. 5).

Inasmuch as radiative heating is the source of the abrupt rise in total heat input at the higher entry velocities, the interplay of vehicle type and entry velocity as they may contribute to the radiative input will be considered briefly. Figure 11 presents an estimate of the ratio of the radiative to the convective heat load for three vehicles as a function of entry velocity[3]. The L/D = 0 vehicle is a hemisphere with a short cylindrical afterbody; the L/D = 1/2 vehicle is of the Apollo type; and the L/D = 1 vehicle is a highly swept delta-planform lifting body entering at high C_L. The overall results are indicative of the reduction in the importance of the radiative input as nose radius is decreased and high lift is employed.

Heat Protection

Figure 12 presents a portion of the heating results in the form of heat load versus heat rate so as to establish in a general way the relation of the stagnation point convective heating to the materials picture. It is sufficient to use entry mode U for this purpose, since mode M produces a more severe environment. The left end of each shaded band corresponds to entry at 26,000 ft/sec and the right end to 46,000 ft/sec. The boundary below and to the left of these data bands is that suggested by Roberts[4] for approximating the limits to which metallic shields can operate; for example, the refractory metals can be expected to cope with some 40 to 50 Btu/ft^2/sec, and a copper heat sink approach would be so heavy in handling heat loads greater than about 10,000 Btu/ft^2 that it would probably not be feasible. Ablation materials of one type or another are capable of handling essentially all heat inputs covered by the figure, although they are not the best approach throughout. The current state of heat protection technology is such that barring unforeseen developments, ablation materials will be the most likely choice for the stagnation region of a multipurpose vehicle.

Of greater concern, perhaps, than the heating of the nose or stagnation region is the heating of the major surface areas of the vehicle. Estimates of the maximum radiation equilibrium temperatures (emissivity of 0.85) that would exist along the streamwise centerline of a delta-planform lifting body with $(L/D)_{max} = 1$, and entering at $C_{L_{max}}$ by mode U, are shown in the left-hand portion of figure 13.

Only the convective input is considered. The hatched bands indicate the range of temperatures to be expected on the lower surface between undershoot (top of band) and overshoot (bottom of band) for the velocities indicated. Note that there is a drop of only a few hundred degrees in progressing 20 feet rearward from the tangency point of the surface with the hemispherical nose.

The curves showing the rapid decay in temperature with distance rearward are for the upper surface centerline and the condition of overshoot. These estimates are subject to greater uncertainty, but they should give some feel for the near-minimum temperatures to be expected on the vehicle.

In the right-hand portion of the figure is given the status of the life of coated refractory metal sheet as summarized by Mathauser[5]. The different curves represent different refractory metals; it is not essential to our purpose to identify each but they include tungsten, tantalum, molybdenum, and columbium, and they represent a generally optimistic average of test information. The broad result is that present-day coatings can provide protection under continuous exposure of at least 1 hour at 3000° F to 100 hours at 2500° F, and that an order of magnitude or greater decrease in coating life is obtained under cyclic exposure conditions. This serious degradation under cyclic temperature exposure reflects directly on the reusability of refractory metal components in entry vehicles. Added to Mathauser's compilation is a band indicating a probable improvement in the picture from future coatings and/or ceramics. However, this hoped-for gain has been promisory for several years now, and has not yet been realized for sheet-type application. Indications are that its achievement will likely be accompanied by short material life or inherent erosion, thereby inferring refurbishment after each entry flight and in this respect would require a refurbishing technique somewhat akin to that for a surface protected by ablation material.

A comparison of the two sides of figure 13 shows that methods of heat protection other than refractory metals will be required over much of the surface area of an entry vehicle if it is to have the prime requisite of multipurpose capability, i.e., good growth potential in entry velocity. (Bear in mind that any radiative input to the surface temperatures that might occur at the higher velocities has been neglected.) At this time, a refurbishable ablation covering appears to offer the best heat protection approach for the multipurpose vehicle concept. A desirable goal is refurbishment by a technique that lends itself to use of coverings of different thickness as mission requirements may dictate. Hopefully the technique would also be able to capitalize readily on new and more efficient ablation materials as they are developed. Refurbishment for lifting vehicles appears to be within the capability of current technology; refurbishable ablation shields have already performed successfully in unmanned ballistic entry.

The effect upon vehicle aerodynamics of the shape changes that accompany ablation might be an area of concern for vehicles that are for the most part ablation-protected. However, for vehicles with low to moderate L/D that do not involve overly small leading-edge radii, nor invade the upper hyperbolic velocity regime, preliminary examinations indicate that adverse effects can be largely circumvented through appropriate design. The same remarks apply to the question of "hinge-line freeze" from possible downstream deposition of ablation products.

As a final comment on the heat-protection picture, much remains to be learned about the performance of all thermal protection schemes during prolonged exposure to space environment. No insurmountable problems have been uncovered for the more promising approaches outside of those created by the impact of meteoritic particles. In this connection, the "ream-and-plug" repair technique currently used on ablation shields appears to offer a reliable solution for these materials. An equally promising technique for repairing the damage to the thin coatings that prevent oxidation of the higher-temperature refractory metals is not yet in hand.

Weight of Entry Vehicles

Over the past few years, a number of system studies have been made of entry vehicles by various industrial organizations. Much of this information is of a proprietary nature, or classified. However, some indications of the results of these studies can be presented herein if confined to a form that respects the interests of the source. For these reasons, the sources of the data in the compilations that follow are not identified.

Figure 14 presents the results of a literature survey of entry vehicle system studies. The studies encompass 1 to 3 man vehicles and 1 to 14 day missions, with entry at or near orbital speed. At the top is shown the variation in the ratio of total entry vehicle weight at finite L/D to that at L/D = 0, i.e., W/W_0. The spread in the band formed by the data at any value of $(L/D)_{max}$ is far less an effect of the crew size and mission time variables than a reflection of differing vehicle types and differing structural and equipment weights. While all studies support the general indication of increasing weight with increasing $(L/D)_{max}$, data from most of the more recent studies fall in the lower part of the data band; this is particularly true at the lower values of $(L/D)_{max}$.

The bottom half of figure 14 gives the variation of the ratio of payload weight to total vehicle weight. The quantitative values are not overly important since these are dependent on what one defines as payload.[3] The trend of the data is the important feature in that it reflects the drop in payload efficiency with increasing $(L/D)_{max}$.

Following this survey of the literature an attempt was made to get a more refined picture of the variation of W/W_0 with $(L/D)_{max}$. The results of these weight estimates are shown in figure 15 together with sketches of the vehicles involved (see ref. 3 for additional information). It is doubtful that the values of W/W_0 can be defended more closely than the height of the symbol bars; however, the overall results are believed to convey a reasonably accurate picture of the relative positions of the different vehicles.

For the results at V_E = 26,000 ft/sec, two primary heat protection methods were considered, ablative and radiating metallic. The method indicated for each vehicle was found to be the lightest approach; the designation $A \sim R$ infers that the choice was not clearly indicated, but tended toward the ablative. The general reduction in the values of W/W_0 with increasing crew size is for the most part simply a reflection of the larger values of W_0, however, crew size does appear to have a significant effect on the variation of W/W_0 with $(L/D)_{max}$. In this regard, multiman requirements appear in most studies of future manned missions; the upper range of interest currently centers on about 12 men. A capacity of this order is therefore believed to be a desirable feature in a multipurpose vehicle, together with the flexibility to interchange crew size with cargo or equipment as the mission requires. If a 12-man capacity is assumed, these results indicate that values of $(L/D)_{max}$ of about 1 or slightly higher can be realized without major increase in weight.

The lower part of figure 15 presents results for an entry velocity of 46,000 ft/sec. All vehicles use ablation as the primary heat protection approach. The low L/D vehicles selected here tend toward conical types since they are believed to be more representative of types suitable for this velocity (e.g., see refs. 1 and 6). For reasons given earlier it is doubtful that vehicles with $(L/D)_{max}$ less than about 0.5 will be considered for manned entry at this velocity. With this in mind, the weight penalty for increasing $(L/D)_{max}$ to about 1 does not appear to be overly large.

As an adjunct to these examinations of entry vehicle weight, figure 16 presents results of a literature search conducted with the aim of exposing effects of entry velocity and heat protection approach on entry vehicle weight. At the bottom is shown the ratio of total vehicle weight for a radiating metallic approach to that for an all or nearly all ablative approach. As would be expected, the trend in moving toward higher entry speeds is to shift the advantage to the ablative approach. As roughly indicated by the wavy lines, the higher the $(L/D)_{max}$, the higher the entry velocity for which the radiating metallic approach remains competitive. These results are restricted to a maximum longitudinal ranging during entry of 10,000 miles. While this seems ample for a multipurpose vehicle, longer ranging would shift the picture in a direction somewhat more favorable to the radiating approach.

At the top of the figure is shown the increase in weight associated with increasing velocity for ablation-protected vehicles having $(L/D)_{max} \approx 1$. The indication that the weight penalty for increased velocity potential is within the realm of practical consideration is at least reassuring in the concept of a multipurpose vehicle.

<u>Lateral Ranging</u>

No attempt will be made to summarize the many facets of lateral ranging at supercircular entry velocities. It seems sufficient to look briefly at the lateral ranging associated with entry at circular velocity by recognizing that increased entry velocity appears to offer no outstanding difficulty in reaching a prescribed landing point, and generally increases the accessible landing area (e.g., see refs. 2 and 7). The material that is presented herein is taken directly from reference 8 in which return from a near-earth orbit is treated. The assumed value of W/C_DS is 200 lb/ft^2; however, the results are relatively insensitive to this parameter, at least to as low as $W/C_DS = 75$. The entry mode is essentially mode U.

At the top of figure 17 is shown the maximum lateral range and hypersonic L/D required for quick return to a specified landing site. By quick return is meant a return with a delay time between decision to enter and initiation of entry of less than one orbit. The ability to reach any point on the globe once each orbit from any orbit inclination is seen to require a hypersonic L/D of about 3.6. On the other hand a variety of interesting combinations of orbit inclination and landing site require considerably less L/D.

If we are satisfied with accepting reasonable delay times in orbit, the hypersonic L/D required can be reduced considerably. For example, consider the polar orbit which is of interest because of the complete earth coverage it affords. In this case, the bottom part of figure 17 shows that a vehicle with a hypersonic L/D of about 0.9 can reach any point on the U. S. mainland twice daily, while an L/D of about 0.7 assures at least once-a-day return.

The relation between delay time and hypersonic L/D required to return to a specified landing site is a strong function of orbit inclination and involves discontinuities, as illustrated in figure 18 for the case of return to Edwards Air Force Base. In this example, as L/D is decreased the equatorial orbit is either a quick-return or no-return proposition, whereas the polar orbit goes from quick return, to a steady increase in holding time, to a discontinuous jump in holding time. The 30° orbit shows some of the characteristics of each of these limiting orbits. Other examinations show that an L/D of about 1 will provide at least once-a-day return to the U. S. mainland from an orbit of any inclination that passes over the mainland (i.e., for the lowly inclined orbits any spot within the southern half of the U. S. would be accessible, and as orbit inclination increases the accessible area increases until the entire U. S. mainland is accessible for orbits inclined greater than about 37°).

A broad look encompassing the areas already discussed tends to direct attention toward entry vehicles with hypersonic $(L/D)_{max}$ in the vicinity of one. Unless quick return capability can be shown to be an essential feature of most future missions, which does not seem to be the case, this same class of vehicles appears to have adequate range capability. For a multipurpose vehicle quick return is of decreasing interest as entry velocity is increased, since the latter usually infers missions that are of longer duration and more remote from earth.

Some mention of the use of space propulsion or air-breathing propulsion to improve lateral ranging seems in order. Briefly, the former appears of interest only for small ranging requirements and vehicles having low hypersonic L/D. The latter appears to be confronted with a dilemma: the primary interest in range augmentation for entry vehicles occurs for the lower L/D vehicles, but in general the lower L/D vehicles do not lend themselves to good inlet performance. Further study is needed to clarify the role of air-breathing propulsion in application to entry vehicles. In any event neither space propulsion nor air-breathing propulsion seem essential to a multipurpose vehicle having moderate hypersonic L/D capability.

Conventional Landing

Low-g impact at landing is desirable for an entry vehicle intended for reuse. Moreover, once hypersonic L/D as high as about 1 is established as a requirement for an entry vehicle, there is the possibility of having conventional landing capability without major weight penalties or severe compromises to hypersonic performance. It is of interest therefore to see what conventional landing may require in subsonic performance. One aspect of the landing problem is considered in figure 19 where a summary of landing approach criteria (just prior to flare) derived from pilots' evaluations is presented in terms of wing loading and subsonic L/D. These results are for a C_L of 0.2, which is representative of the lower values of C_L encountered at this point in the landing approach. One must recognize that everything is relative in defining the zones, poor, fair, and good; the boundaries between the zones are fuzzy at best.

Nevertheless, these results show logical trends and should be adequate for approximating desirable objectives. For example, a multipurpose 12-man entry vehicle with hypersonic L/D of about 1 would likely have a wing loading no less than 35, and probably higher; in this case a subsonic L/D of about 4 or more would be a desirable but not necessarily an essential goal.

The ratio of C_L at touchdown to C_L at subsonic $(L/D)_{max}$ is also important in determining the ease with which the landing flare may be accomplished. Similar evaluations of this criterion show a preference for a subsonic L/D of about 4 or greater.

The availability of a modest amount of rocket thrust augmentation appears to offer attractive possibilities for increasing the effective subsonic L/D during approach to landing, and for executing a go-around if required. However, the use of rocket propulsion to increase ranging potential beyond that involved in a go-around soon involves major weight penalties. The potential of variable-geometry schemes for increasing subsonic L/D at small expense in weight deserves consideration[9].

$(L/D)_{max}$ and Volume

The foregoing discussion raises the question: Is conventional landing attainable without severe compromise to volumetric efficiency? One facet of this question is considered in figure 20 where a literature survey of experimental studies of fixed-geometry entry vehicles gives a feel for the interplay of hypersonic and subsonic $(L/D)_{max}$

with volumetric efficiency. The boundaries denoting constant values of the volumetric efficiency parameter are maxima in the following sense: a given valued boundary could move down or to the left, but it is highly unlikely that it could move up or to the right. The form of the boundaries in the transition from horizontal to vertical is open to question. The overall results show that hypersonic $(L/D)_{max}$ comes at greater expense to volumetric efficiency than does subsonic $(L/D)_{max}$. Of particular interest with regard to landing conventionally is the indication that a fixed geometry entry vehicle with hypersonic $(L/D)_{max}$ near 1 is capable of achieving subsonic $(L/D)_{max}$ in excess of 4 while retaining good volumetric efficiency. Other examinations have indicated that reasonably good volume distribution can be achieved in a vehicle that has these characteristics.

Concluding Remarks

The areas touched upon in this review demonstrate that the factors influencing the design of a multipurpose manned entry vehicle that is capable of entry at circular to moderately hyperbolic velocities are numerous and varied, and on occasion lead to conflicting interests. While in some respects better definitions of future missions are needed before a well-founded recommendation can be made of the vehicle class that is best suited for multipurpose use, the results that have been presented herein, when viewed in their entirety, tend to draw attention toward vehicles having a hypersonic $(L/D)_{max}$ in the vicinity of one. The concept of a multipurpose manned entry vehicle appears to be technically feasible, at least to the degree that such a vehicle merits further consideration in assessing how best to meet the requirements that future manned space missions will place upon entry vehicles.

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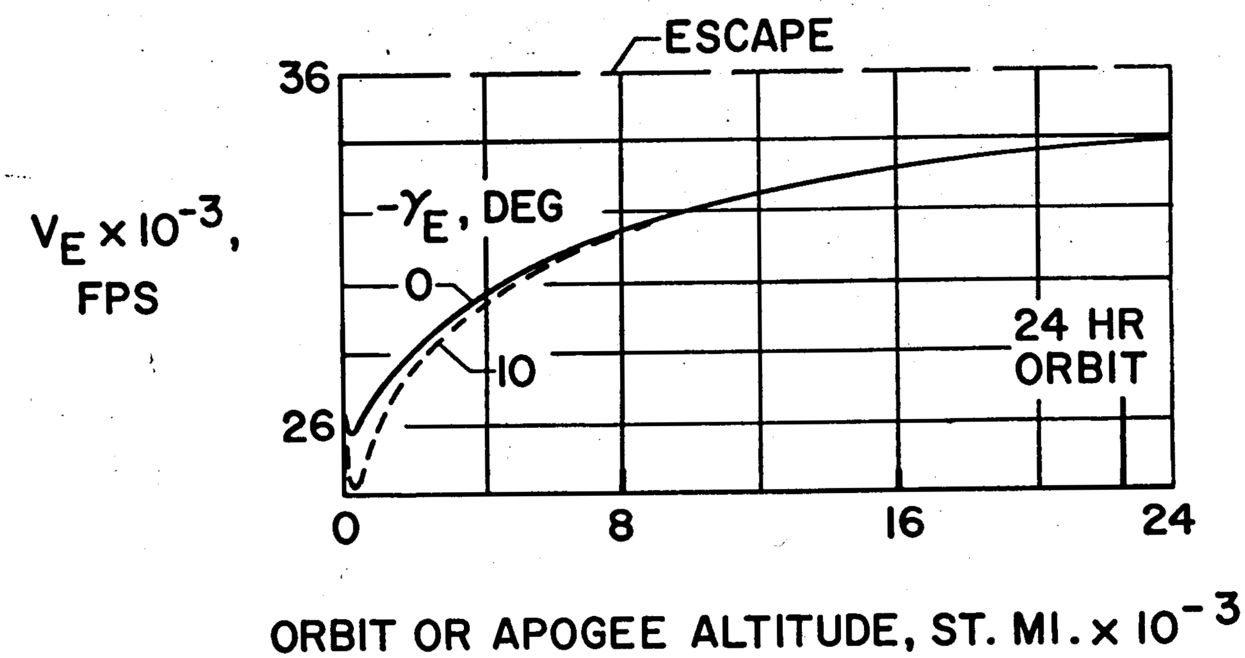

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Figure 1.- Effect of orbit or apogee altitude on entry velocity.

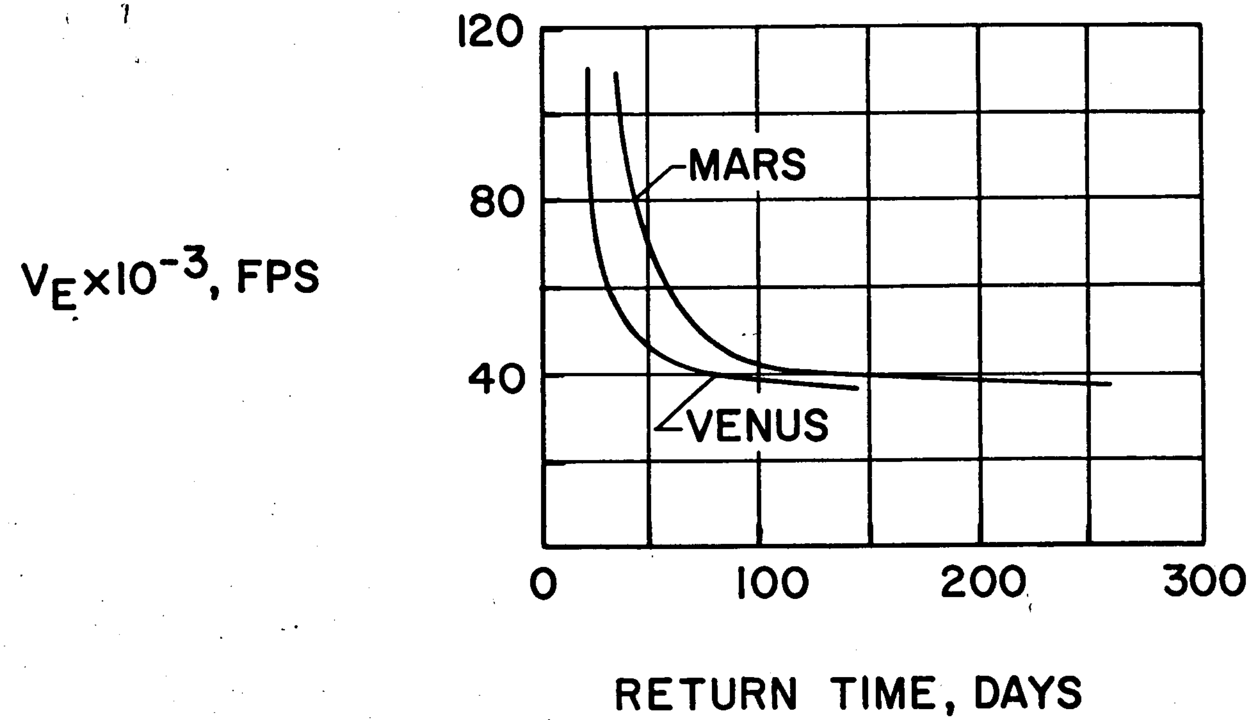

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Figure 2.- Relation of transit time from Mars and Venus to minimum Earth entry velocity.

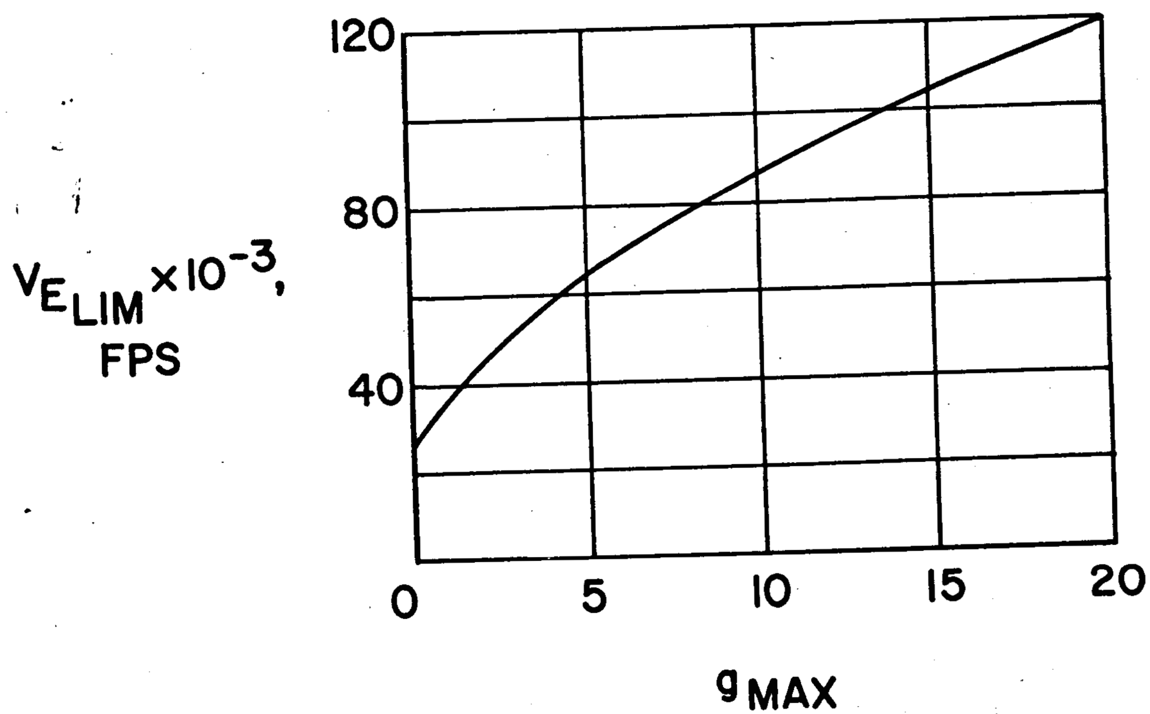

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Figure 3.- Effect of deceleration on limiting entry velocity.

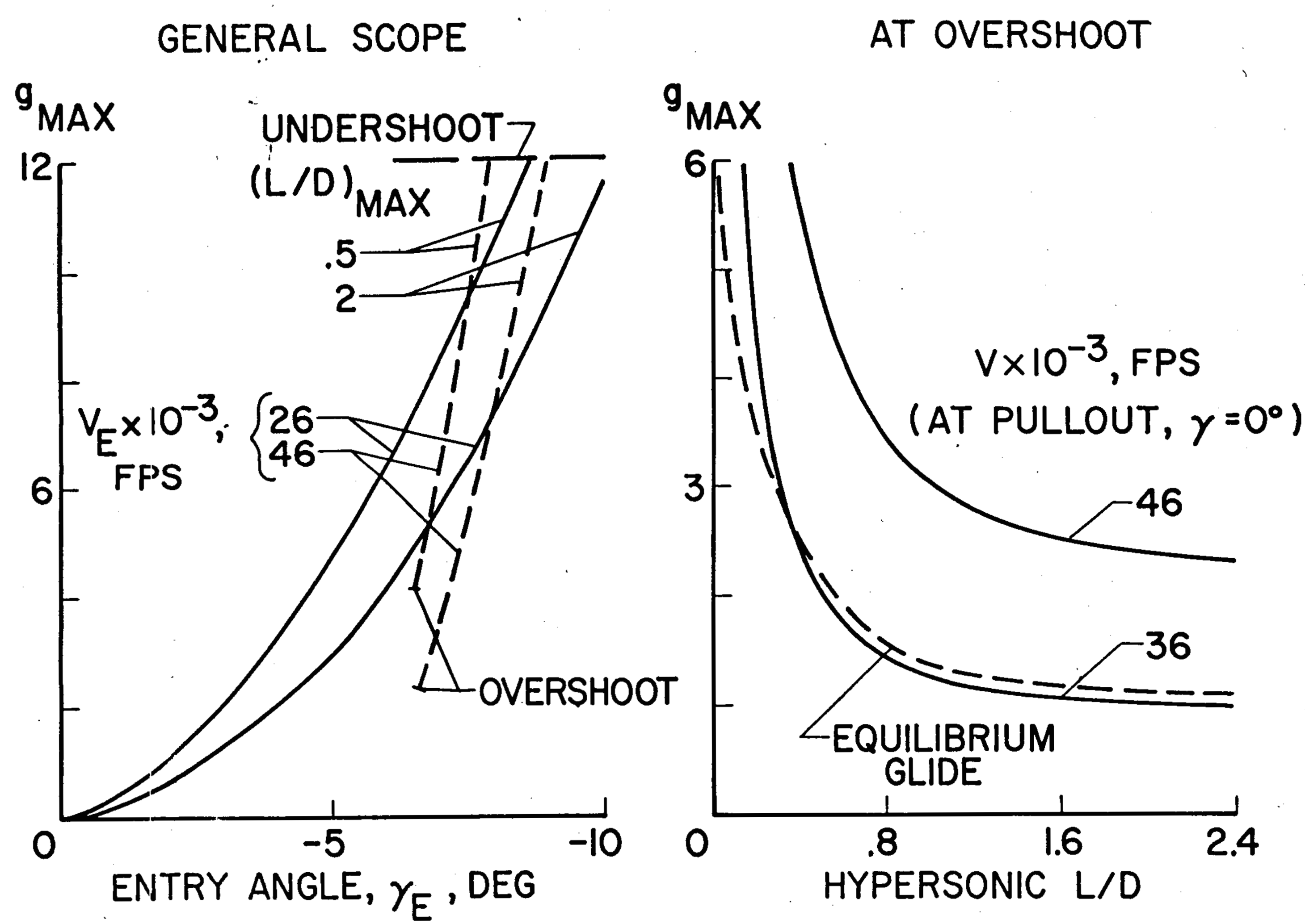

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Figure 4.- Deceleration during entry. Mode U.

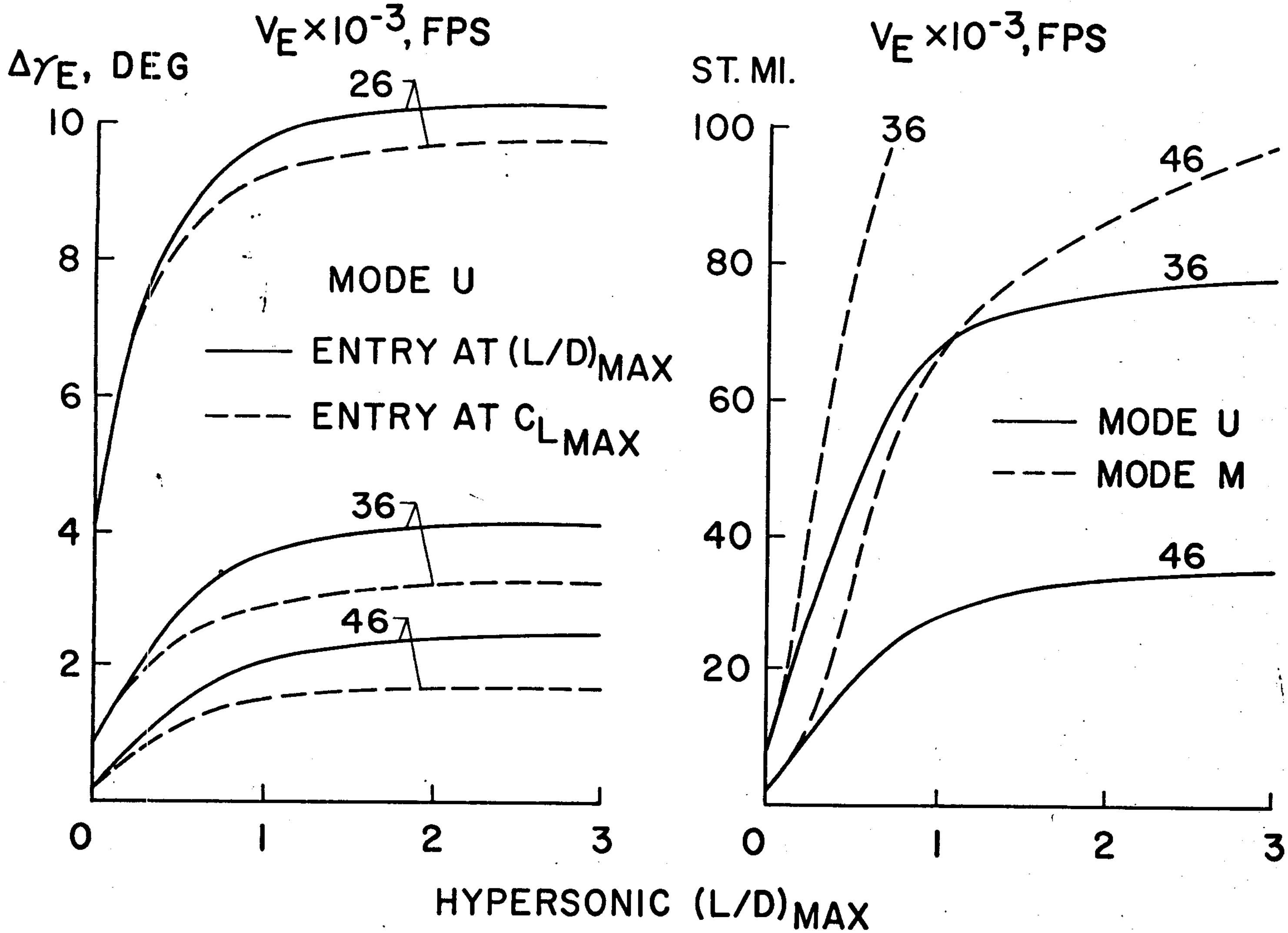

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Figure 5.- Entry corridor width.

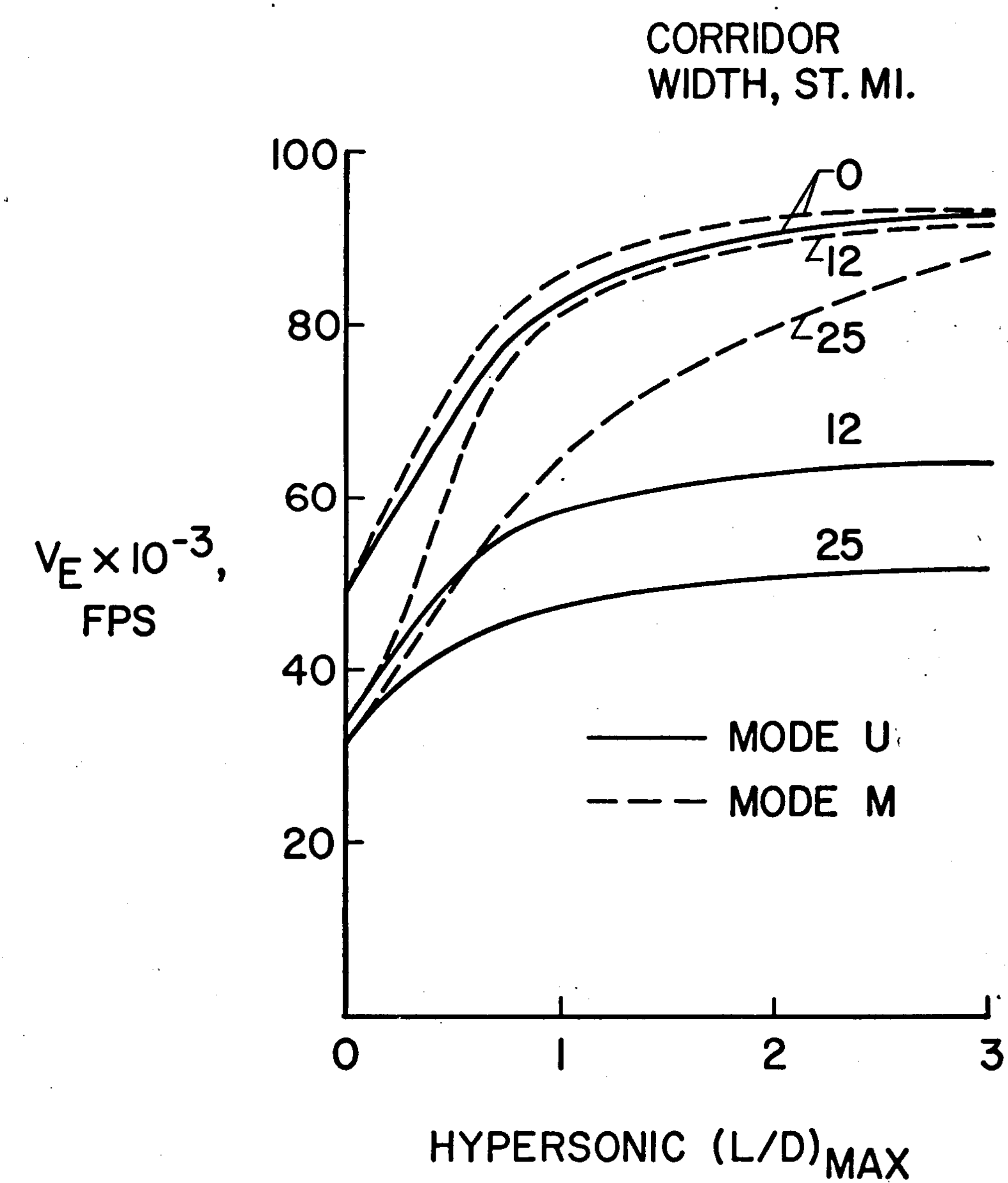

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Figure 6.- Effect of L/D, corridor width, and entry mode on permissible entry velocity.

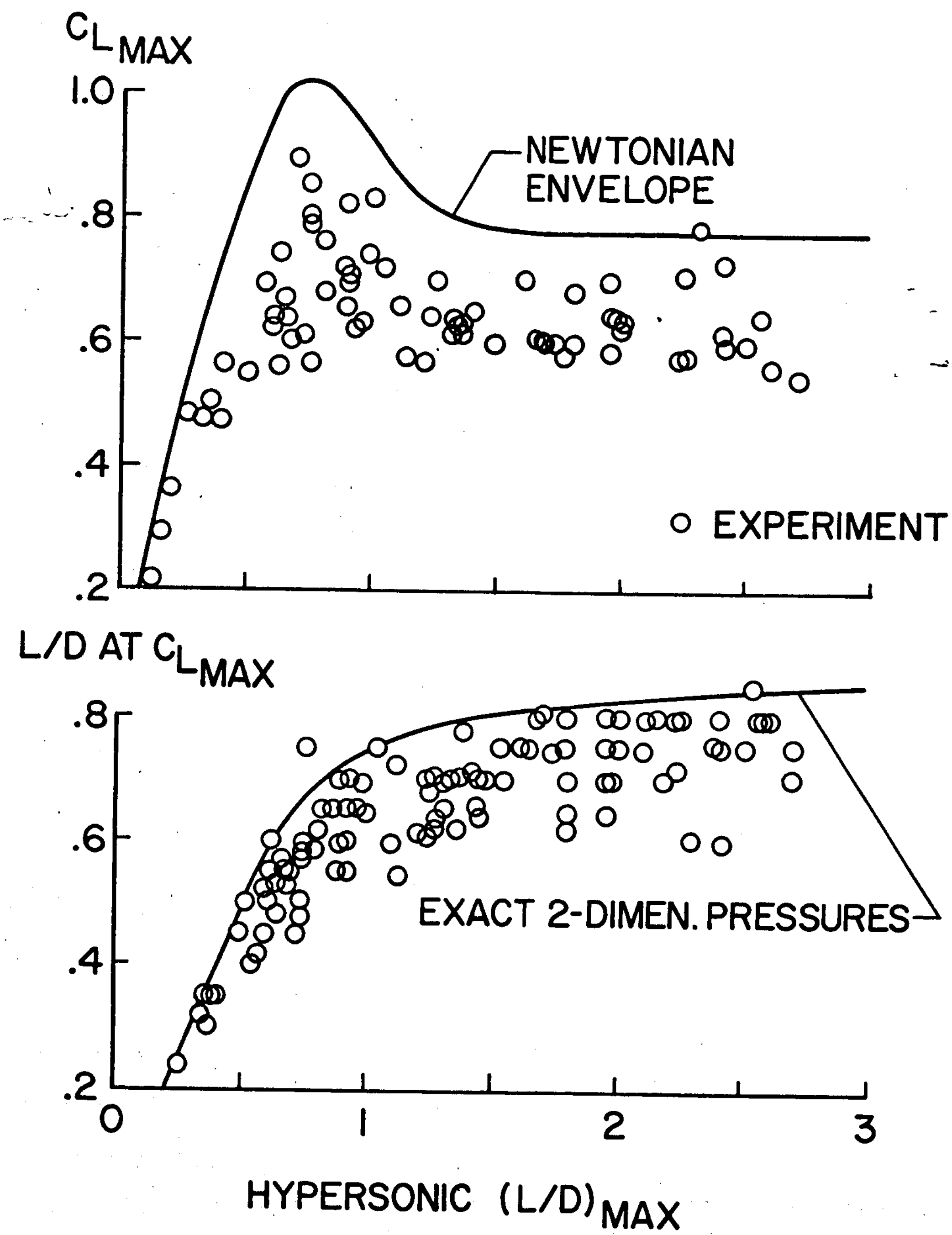

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Figure 7.- Relation of $(L/D)_{MAX}$ to $C_{L_{MAX}}$ and to L/D at $C_{L_{MAX}}$ for entry vehicles.

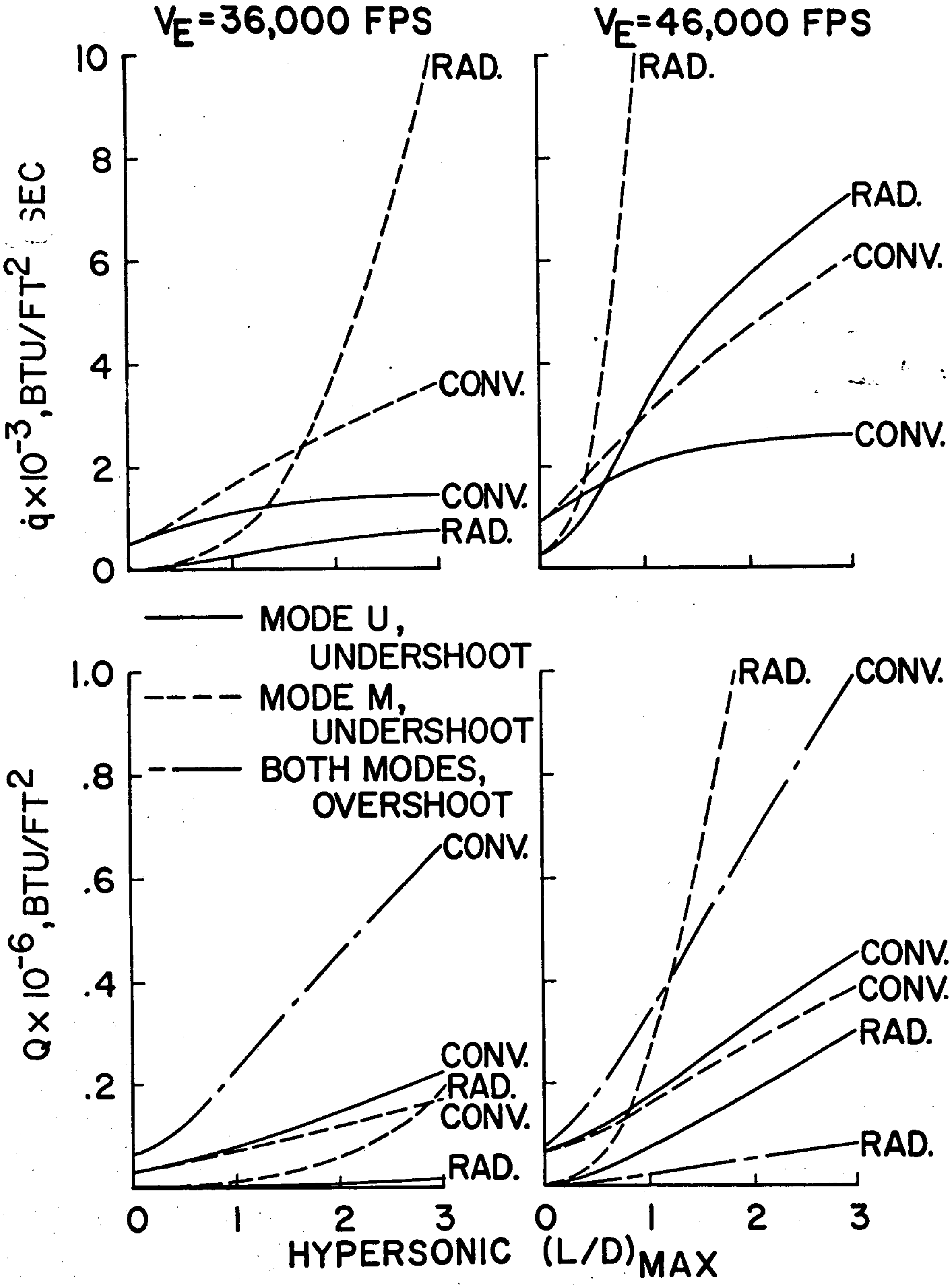

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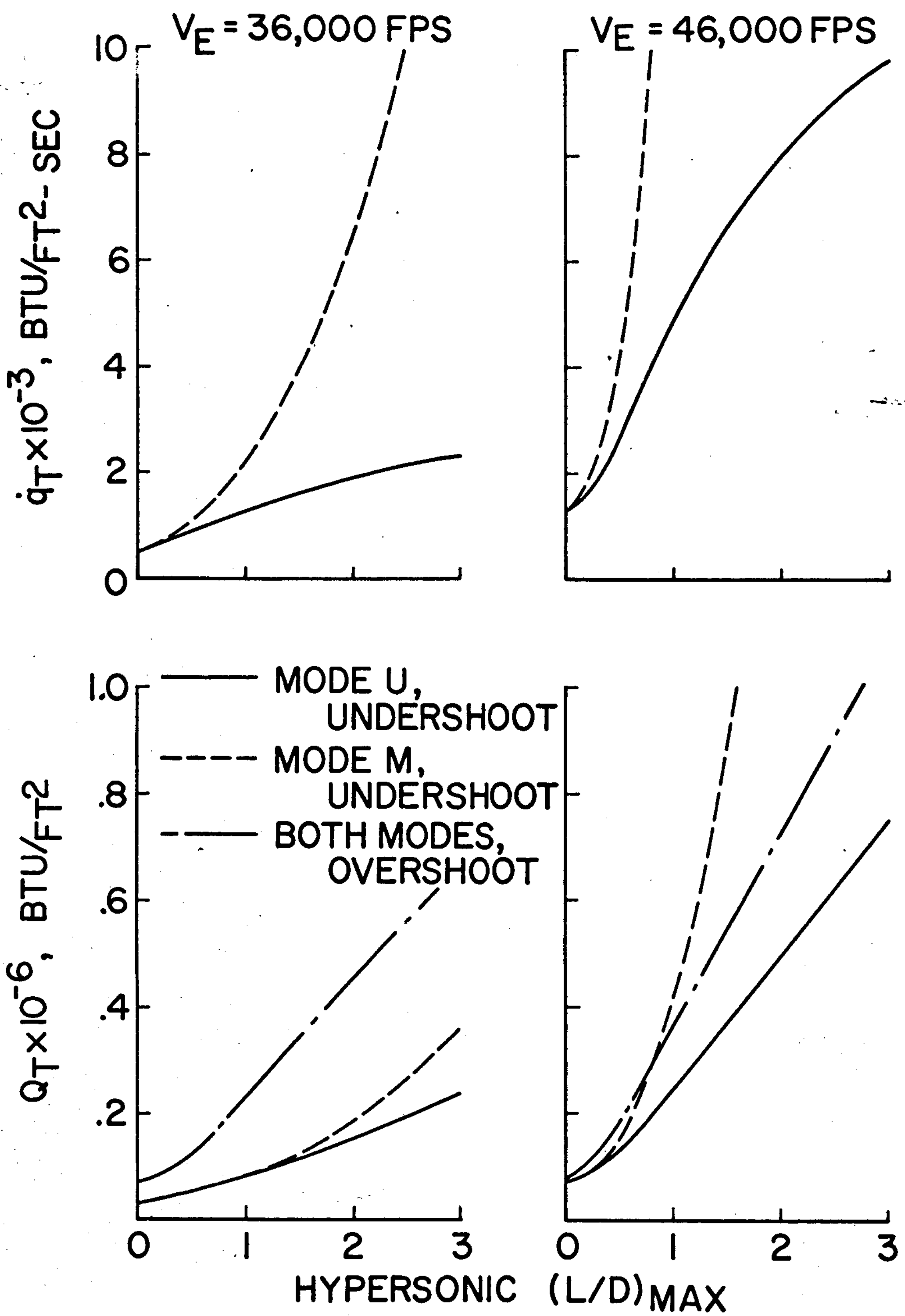
Figure 8.- Maximum stagnation-point heat rates and heat loads. Entry at $(L/D)_{MAX}$.



NASA

Figure 9.- Total maximum stagnation-point heat rates and heat loads (radiative plus convective). Entry at $(L/D)_{MAX}$.

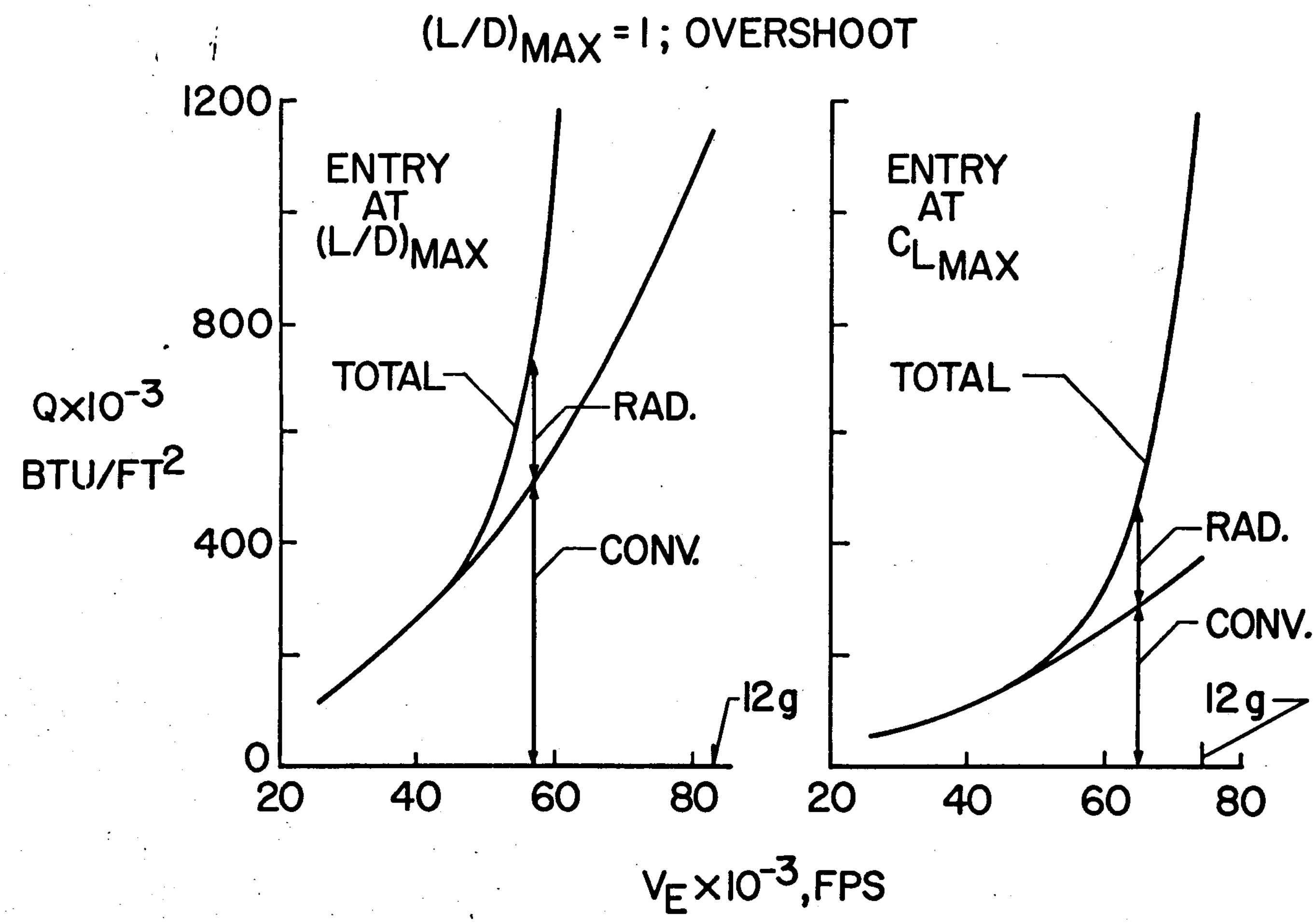


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Figure 10.- Comparison of stagnation-point heat load for entry at $(L/D)_{MAX}$ and at $C_{L_{MAX}}$. Entry mode U.

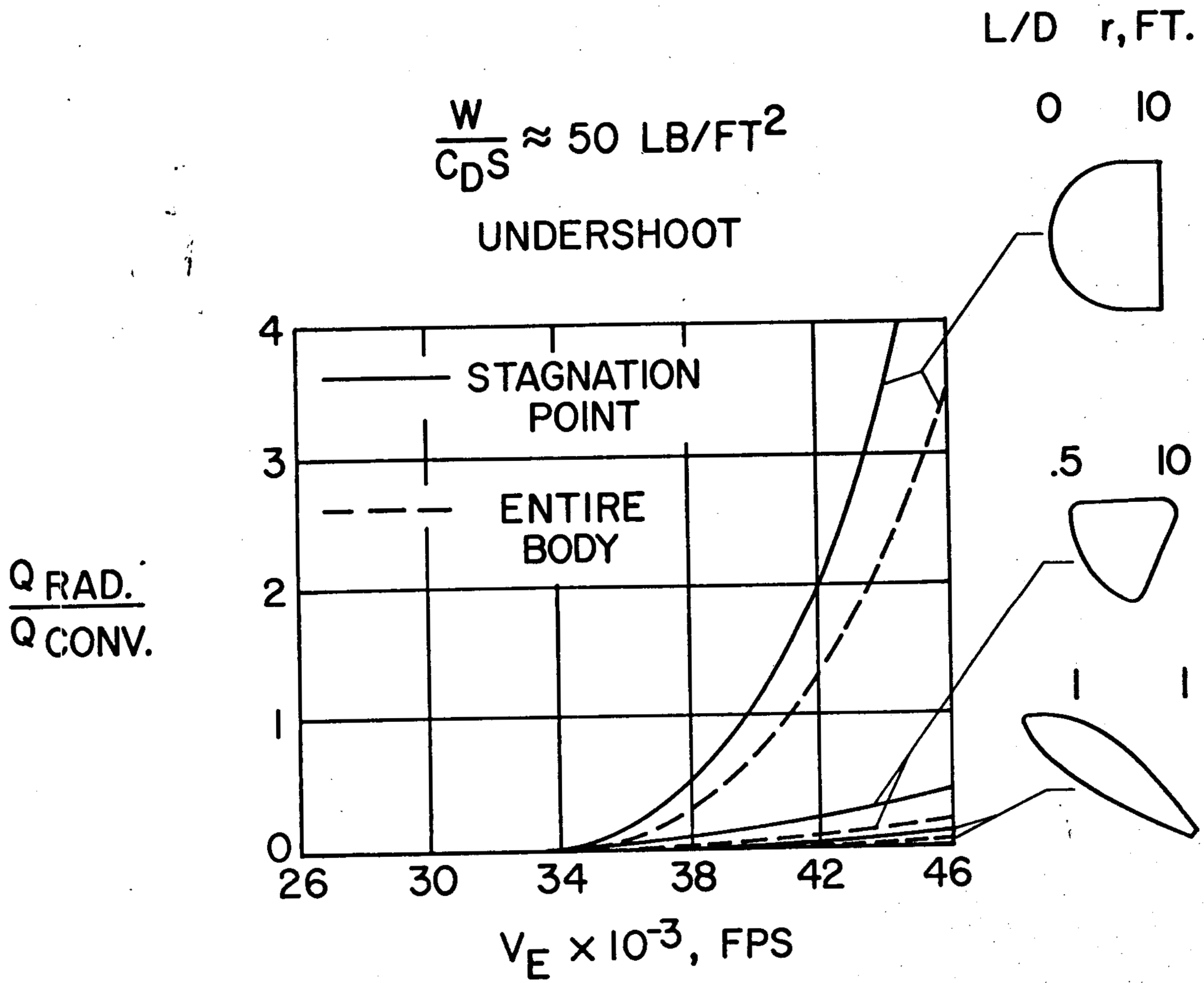

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Figure 11.- Effect of entry velocity and vehicle type on radiative heating contribution.

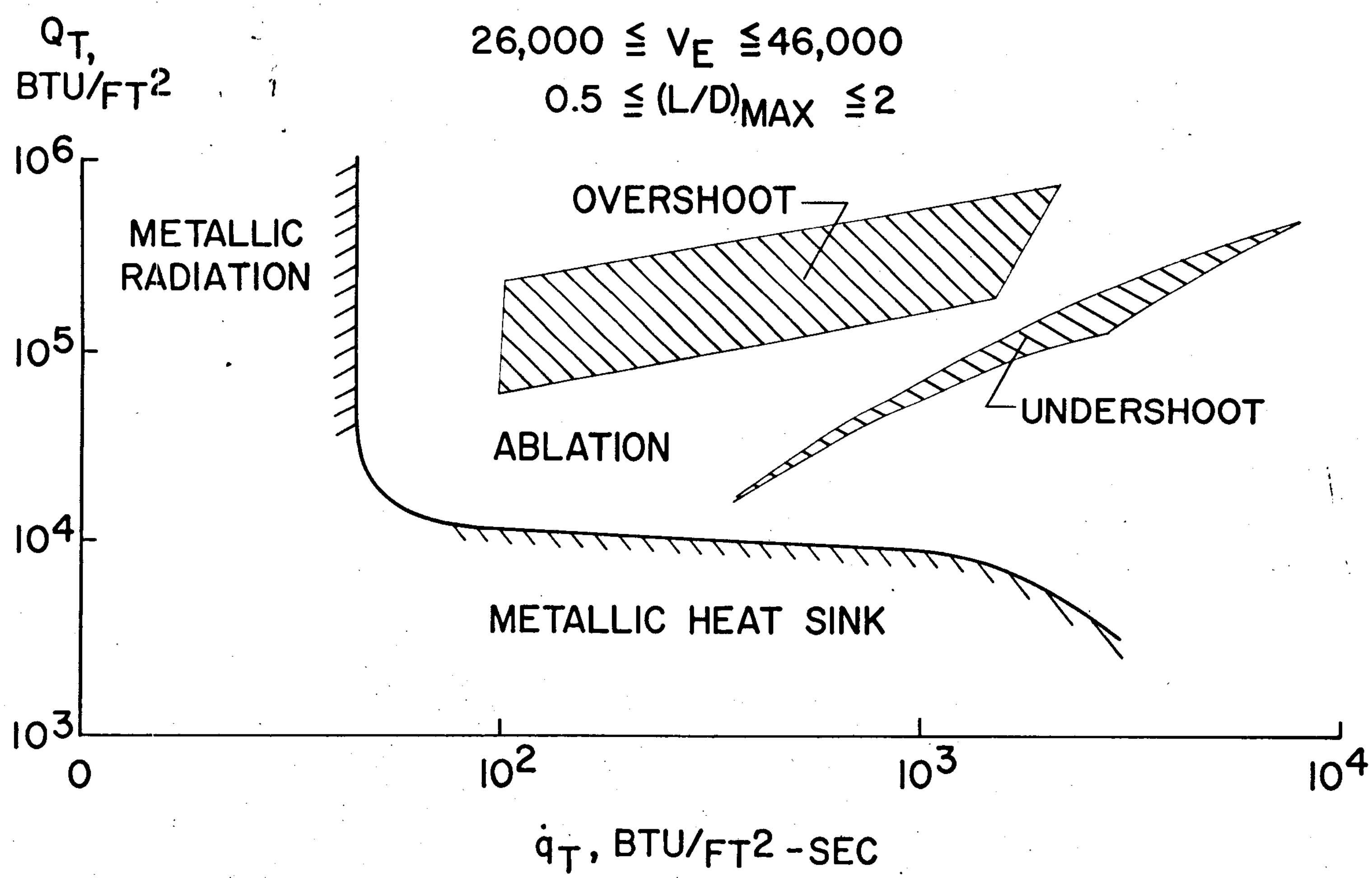

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Figure 12.- Total stagnation-point heating in relation to heat protection. Entry at $(L/D)_{MAX}$, mode U.

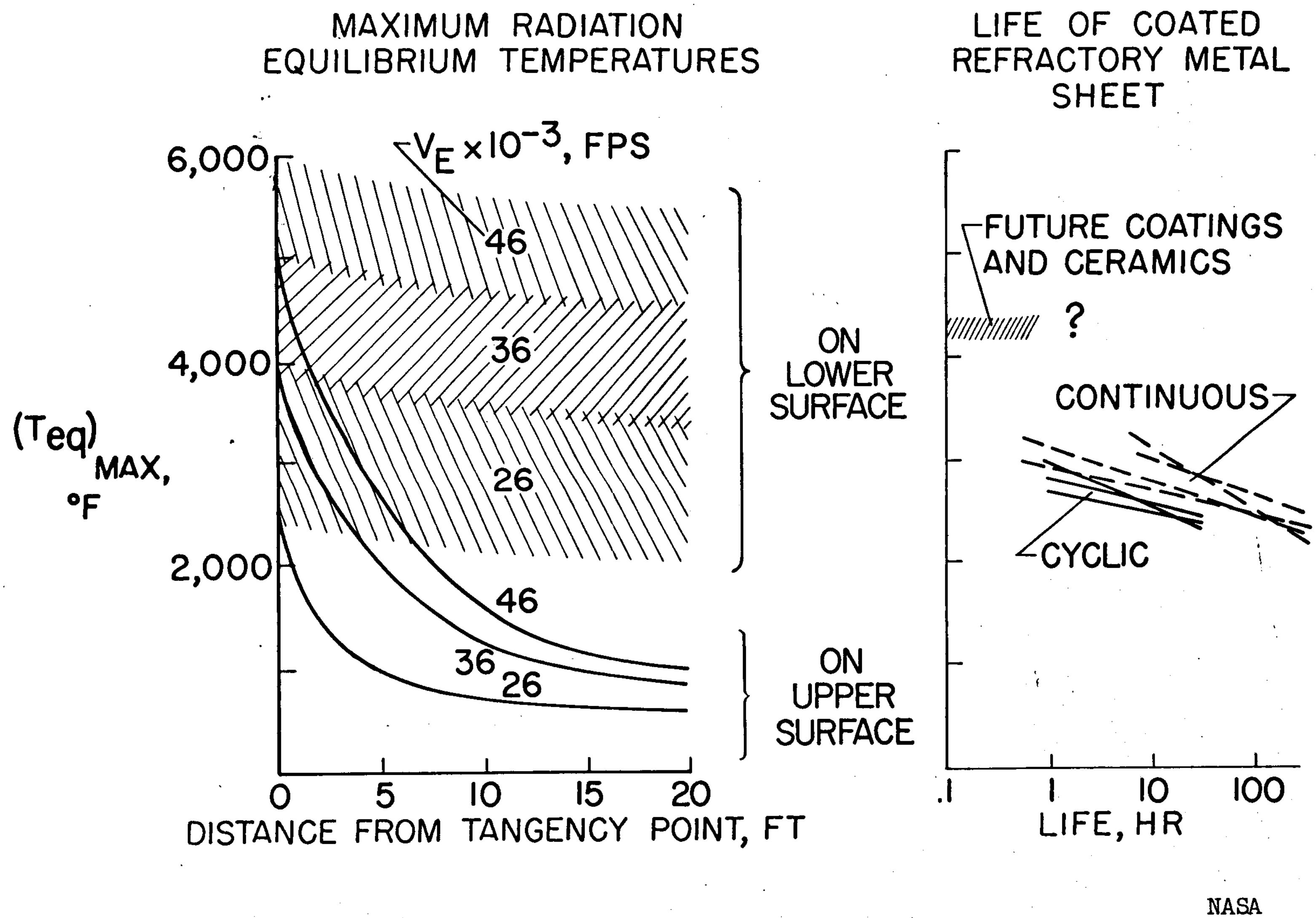

Figure 13.- Surface temperatures and material capability.

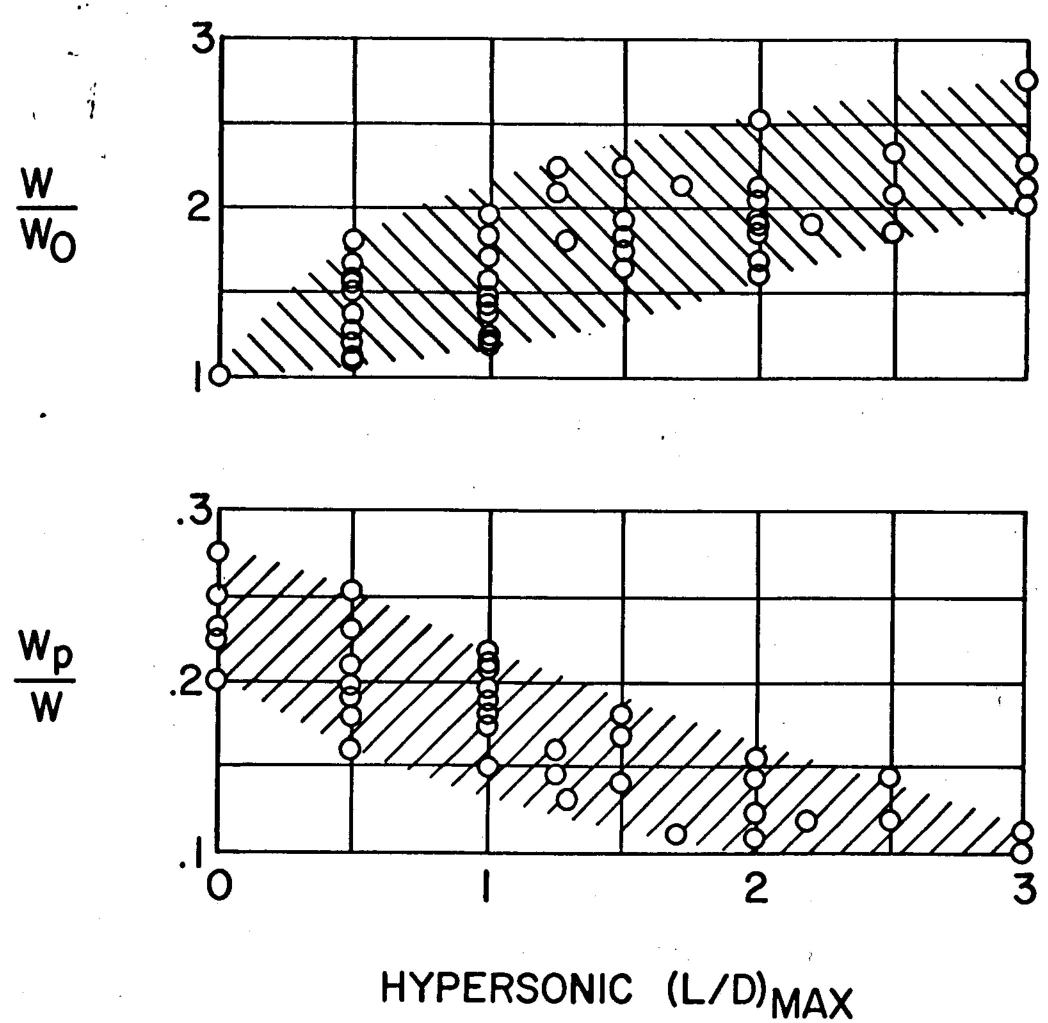

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Figure 14.- Effect of hypersonic $(L/D)_{MAX}$ on entry vehicle weight. Literature survey. $V_E \approx 26{,}000$ fps.

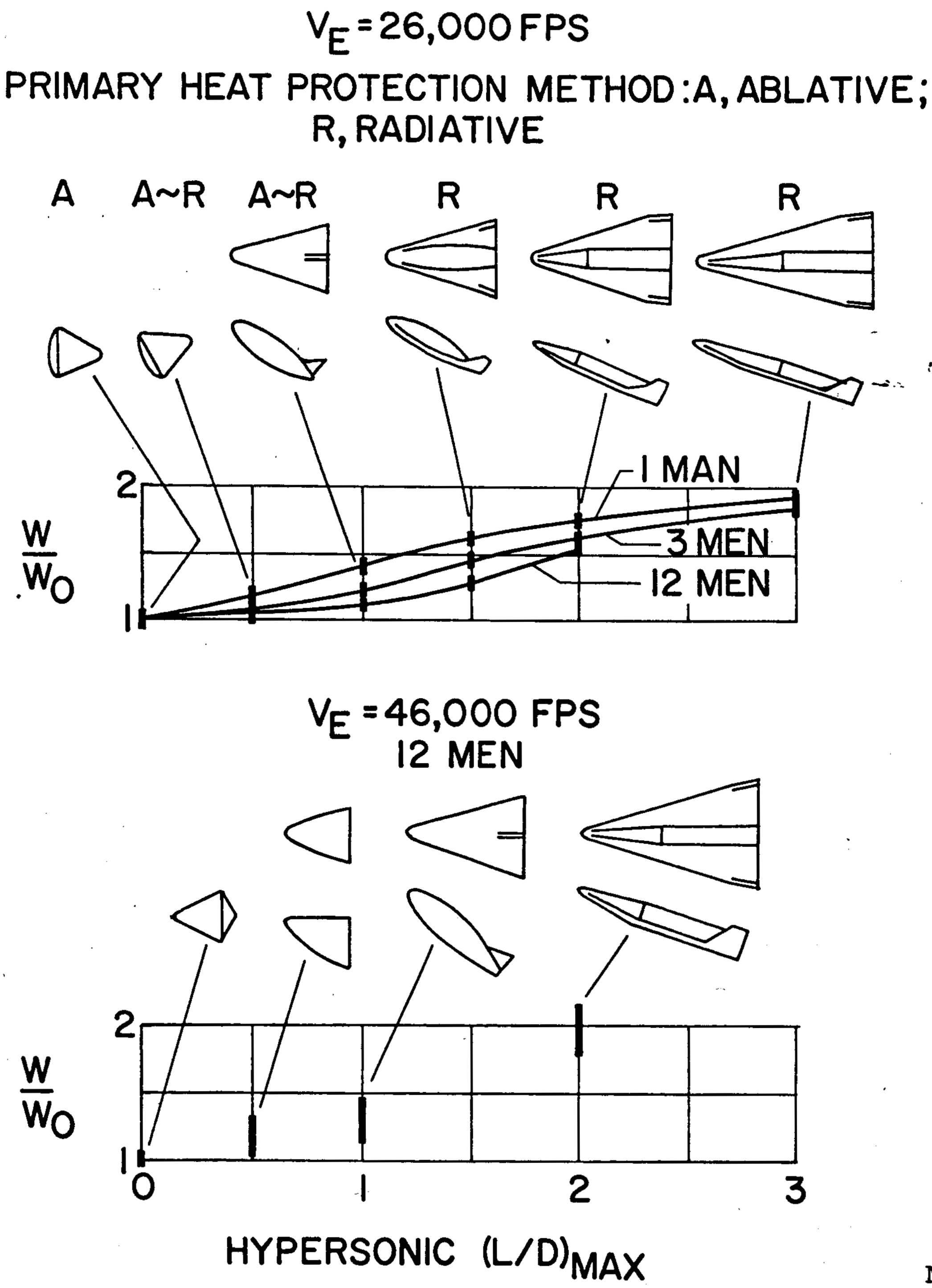

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Figure 15.- Effect of hypersonic $(L/D)_{MAX}$ on entry vehicle weight.

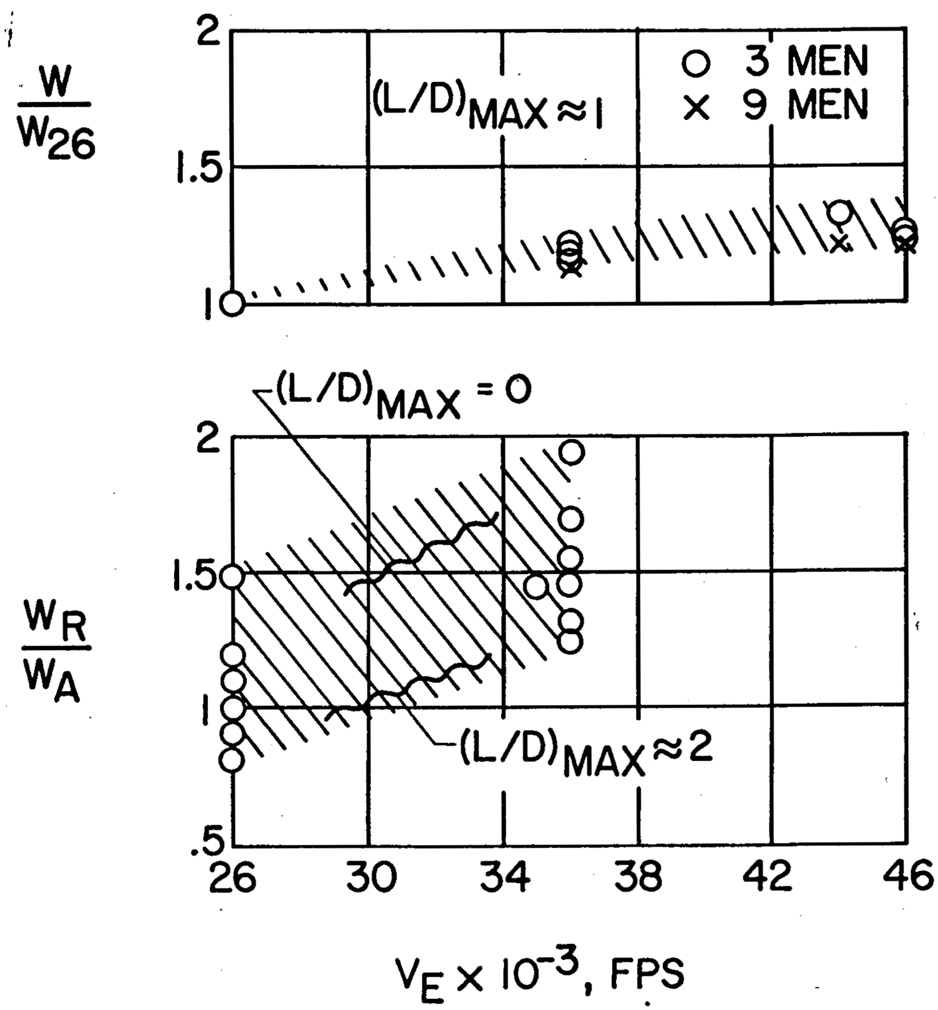

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Figure 16.- Effect of entry velocity on entry vehicle weight. Literature survey.

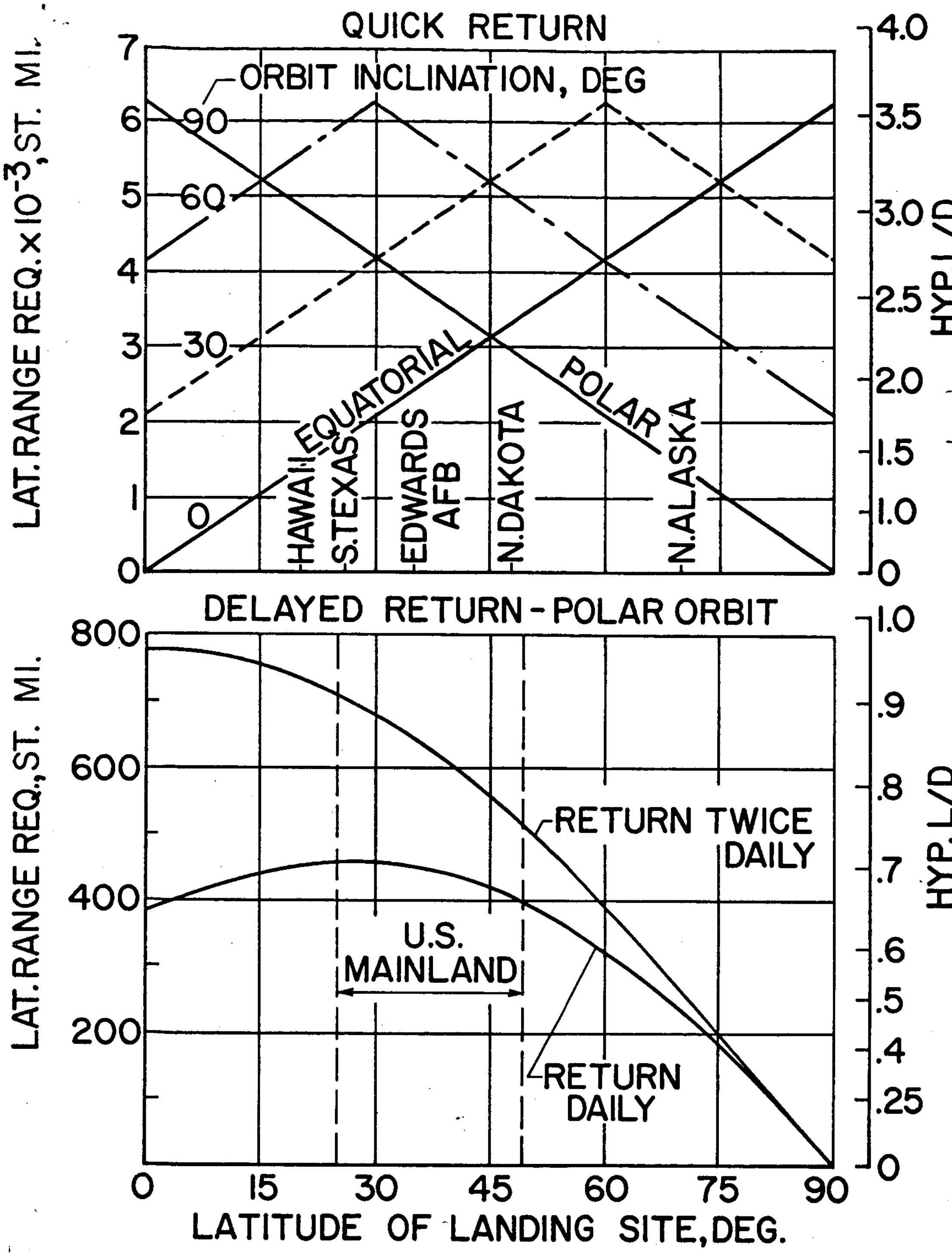

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Figure 17.- Lateral range and hypersonic L/D required for return from near-Earth orbit.

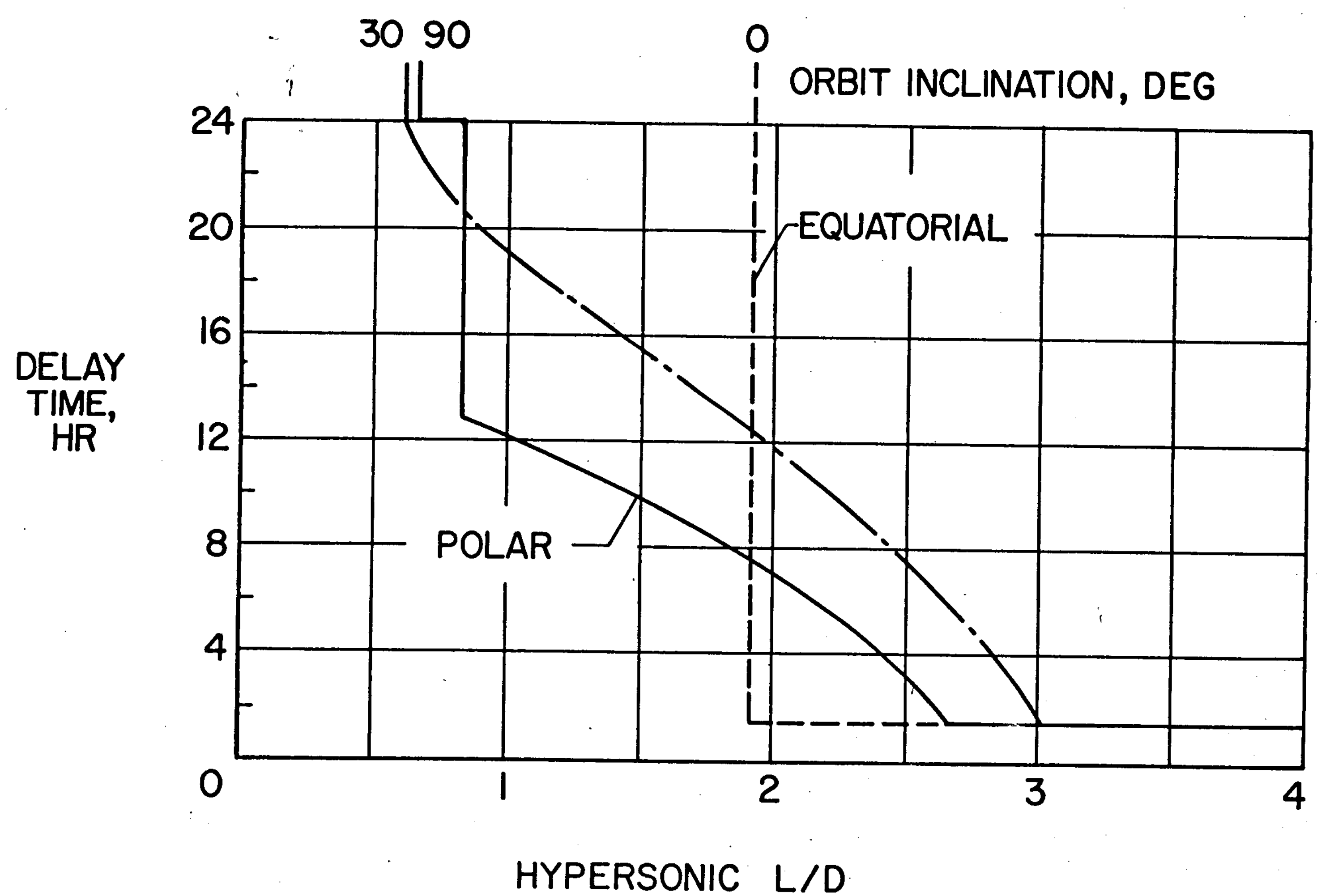

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Figure 18.- Maximum d. ay time for return to Edwards Air Force Base.

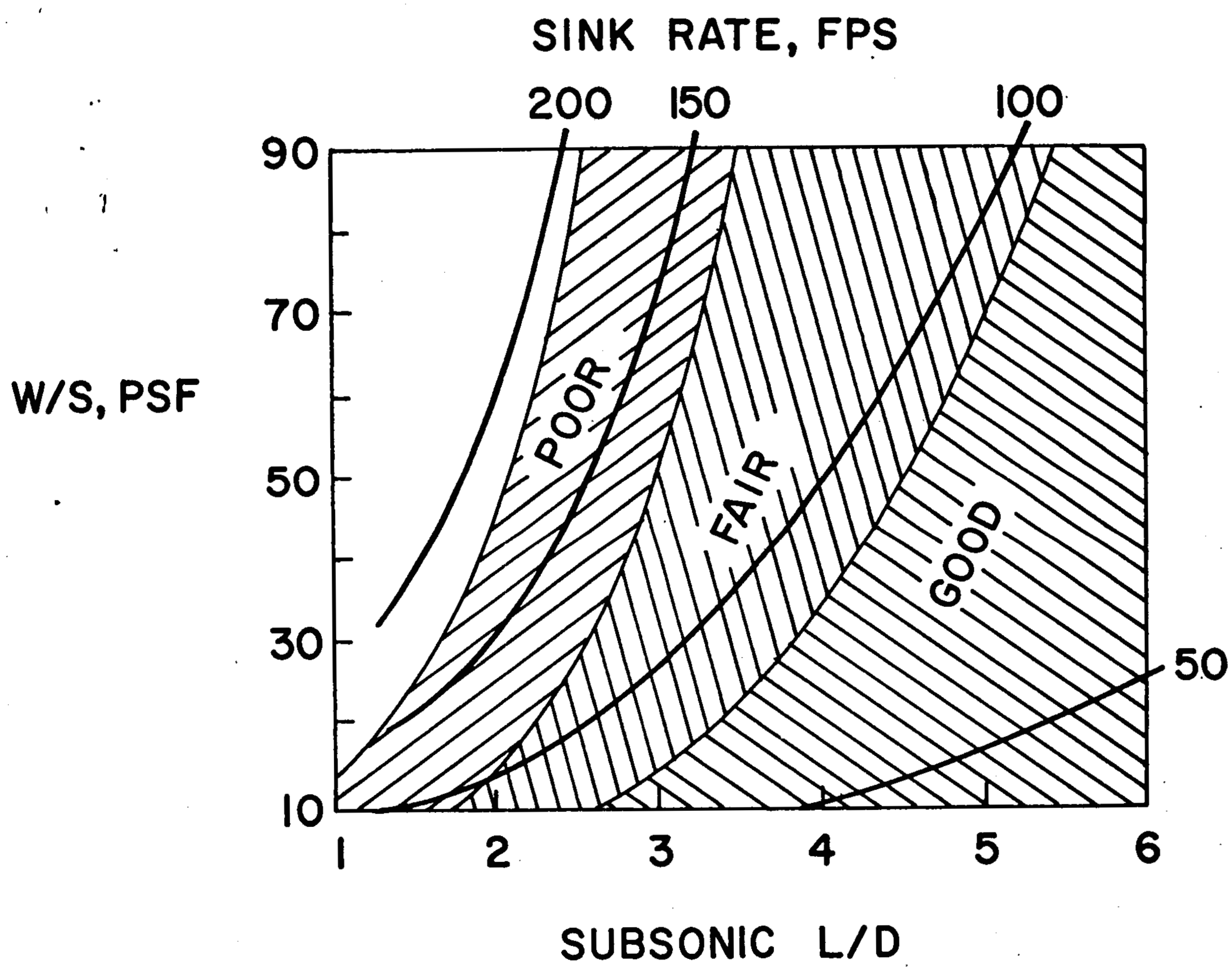

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Figure 19.- Landing approach criteria from pilots' evaluations. $C_L = 0.2$.

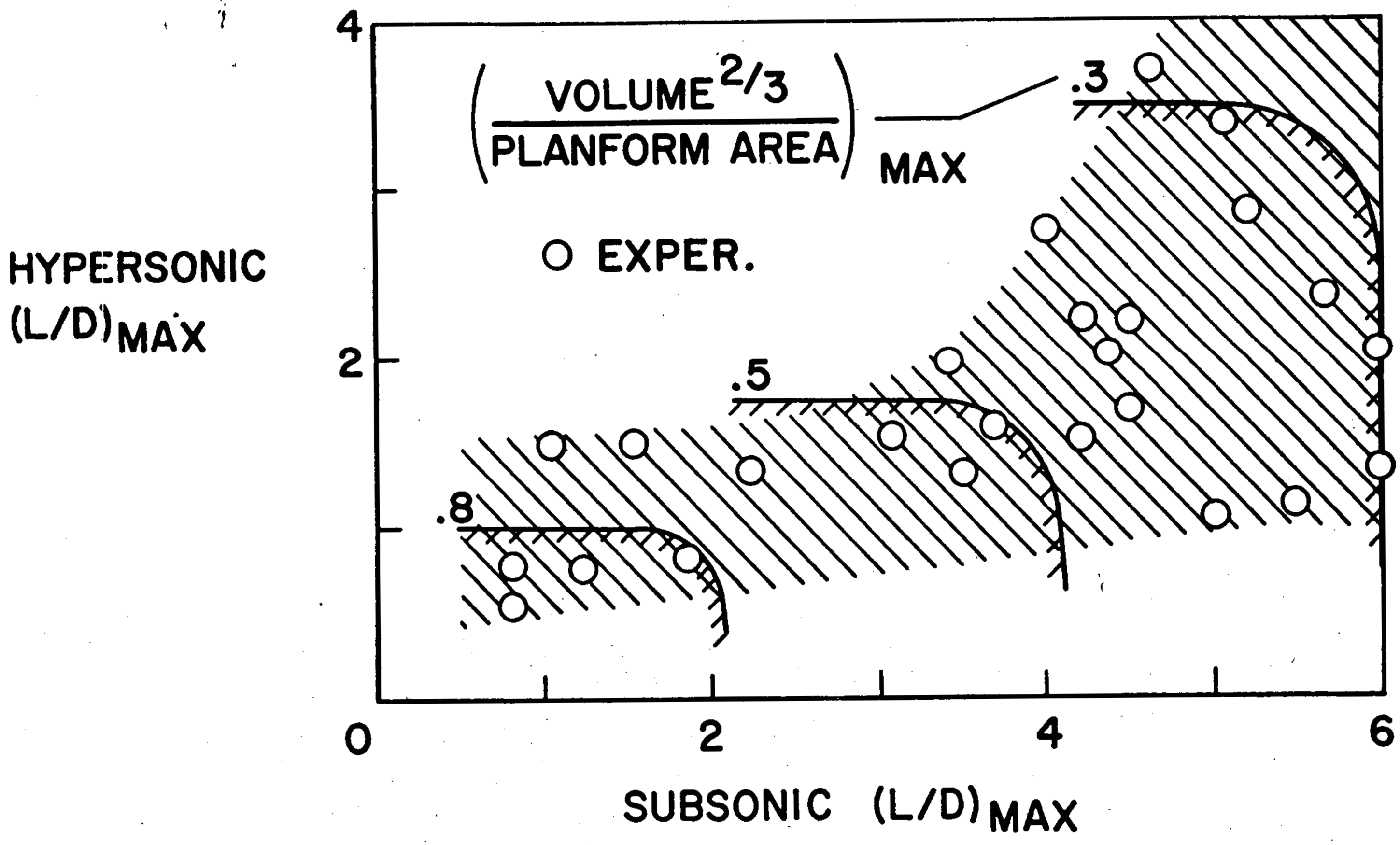

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Figure 20.- Relation of hypersonic to subsonic $(L/D)_{MAX}$ for entry vehicles.

LIST OF FIGURE CAPTIONS

(JSR Paper by E. S. Love)

Figure 1.- Effect of orbit or apogee altitude on entry velocity.

Figure 2.- Relation of transit time from Mars and Venus to minimum earth entry velocity.

Figure 3.- Effect of deceleration on limiting entry velocity.

Figure 4.- Deceleration during entry. Mode U.

Figure 5.- Entry corridor width.

Figure 6.- Effect of L/D, corridor width, and entry mode on permissible entry velocity.

Figure 7.- Relation of $(L/D)_{max}$ to $C_{L_{max}}$ and to L/D at $C_{L_{max}}$ for entry vehicles.

Figure 8.- Maximum stagnation-point heat rates and heat loads. Entry at $(L/D)_{max}$.

Figure 9.- Total maximum stagnation-point heat rates and heat loads (radiative plus convective). Entry at $(L/D)_{max}$.

Figure 10.- Comparison of stagnation-point heat load for entry at $(L/D)_{max}$ and at $C_{L_{max}}$. Entry mode U .

Figure 11.- Effect of entry velocity and vehicle type on radiative heating contribution.

Figure 12.- Total stagnation-point heating in relation to heat protection. Entry at $(L/D)_{max}$, mode U.

Figure 13.- Surface temperatures and material capability.

Figure 14.- Effect of hypersonic $(L/D)_{max}$ on entry vehicle weight. Literature survey. $V_E \approx 26,000$ fps.

Figure 15.- Effect of hypersonic $(L/D)_{max}$ on entry vehicle weight.

Figure 16.- Effect of entry velocity on entry vehicle weight.
Literature survey.

Figure 17.- Lateral range and hypersonic L/D required for return from near-earth orbit.

Figure 18.- Maximum delay time for return to Edwards Air Force Base.

Figure 19.- Landing approach criteria from pilots' evaluations. $C_L = 0.2$.

Figure 20.- Relation of hypersonic to subsonic $(L/D)_{max}$ for entry vehicles.